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DTRC-SME-89/67 Through-Thickness Strain Response of Thick Composites in Compression

Through-Thickness Strain Response of Thick Composites in Compression

by

E.T. Camponeschi, Jr.

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With the continued success of composite materials in high performance structures, new applications for Navy primary structure are being identified. Many of these applications require designs with composite materials having section thicknesses greater than those that have been used and studied to date. Along with this interest in thick composite structures comes the need for full three-dimensional stress analysis. The limits and accuracy of existing three-dimensional data bases will dictate the limit and accuracy of corresponding analyses.

This report summarizes an investigation of the through-thickness strain response of thick composite materials subjected to compressive loading. One-half inch thick (96 ply) carbon and S2 glass reinforced composites were studied. A thick-section compression test method has been developed for the purposes of this investigation. Using this test method the longitudinal and through-thickness

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ABBREVIATIONS

C.V.	Coefficient of variation
DTRC	David Taylor Research Center
E_i	i-direction modulus of elasticity
FVF	fiber volume fraction
G_{ij}	ij-plane shear modulus of elasticity
Msi	one-million pounds per square inch
NU_{ij}	ij-plane Poisson's ratio
psi	pounds per square inch

ABSTRACT

With the continued success of composite materials in high performance structures, new applications for Navy primary structure are being identified. Many of these applications require designs with composite materials having section thicknesses greater than those that have been used and studied to date. Along with this interest in thick composite structures comes the need for full three-dimensional stress analysis. The limits and accuracy of existing three-dimensional data bases will dictate the limit and accuracy of corresponding analyses.

This report summarizes an investigation of the through-thickness strain response of thick composite materials subjected to compressive loading. One-half inch thick (96 ply) carbon and S2 glass reinforced composites were studied. A thick-section compression test method has been developed for the purposes of this investigation. Using this test method the longitudinal and through-thickness strain to failure, longitudinal modulus, inplane and through-thickness Poisson's ratio, and ultimate strength of these materials have been determined. The through-thickness data from the 96 ply [0] coupons show the materials to be transversely isotropic. The through-thickness data from 96 ply [0/0/90] laminates show good correlation with a theoretical solution that provides the nine elastic constants for thick orthotropic plates.

ADMINISTRATIVE INFORMATION

This work was performed as a DTRC Independent Research Program, sponsored by the Office of Naval Research and administered by the Research Director, DTRC 0113, under Program Element 61152N and Work Unit 1-1720-476.

INTRODUCTION

The compressive response of fiber-reinforced composite materials has been the subject of numerous investigations over the past 25 years. Although these investigations have improved the understanding of how these materials respond to compressive loads, the emphasis of these investigations have been on materials less than 0.25 inches thick [1].

With the continued success of composites in high performance structures and the reduction of fabricated costs due to improved manufacturing methods, more applications are being identified. Many of these applications require design of composite materials with section thicknesses greater than those with which engineers have design experience and confidence. Increases in required material thicknesses requires additional analysis procedures at both the material level and the structural level.

In many instances two-dimensional stress analyses will not be appropriate in analyzing thick composite materials and structures. Three-dimensional analysis requires full three-dimensional material characterization. The limits and accuracy of existing three-dimensional data bases will dictate the limit and accuracy of corresponding analyses.

In light of the need for three-dimensional materials characterization, this paper summarizes an investigation of the through-thickness strain response of thick composite materials subjected to compressive loading.

EXPERIMENTAL PROCEDURE

DESCRIPTION OF TEST METHOD

In order to evaluate the through-thickness strain response of composite coupons, a specimen thickness of 0.5 inches thick was necessary. The development of a fixture to test these specimens in compression was necessary and the following criteria were applied: the fixture must allow thick-section testing capability beginning at 0.25 inches, must allow further scale up for thicker, wider, and longer specimens, must prevent load eccentricities, must allow an unsupported gage length, and must prevent splitting or brooming failures from occurring near the load introduction points.

A cross section of the fixture designed to meet the above criteria is shown in Fig. 1. Load is introduced through the end of the specimen. This method of load introduction is more desirable for thick composites than shear load introduction since transfer of load through shear would require large tabbed areas to reduce the shear stress in the tab adhesive. The size, complexity and resulting expense of fixtures designed to introduce load through shear precluded their design and use for this program.

The clamping blocks on the ends of the specimen are held secure to the specimen by through-bolts that provide appropriate clamping force. A hardened steel plate is inserted between both ends of the specimen and the test machine crosshead platens and

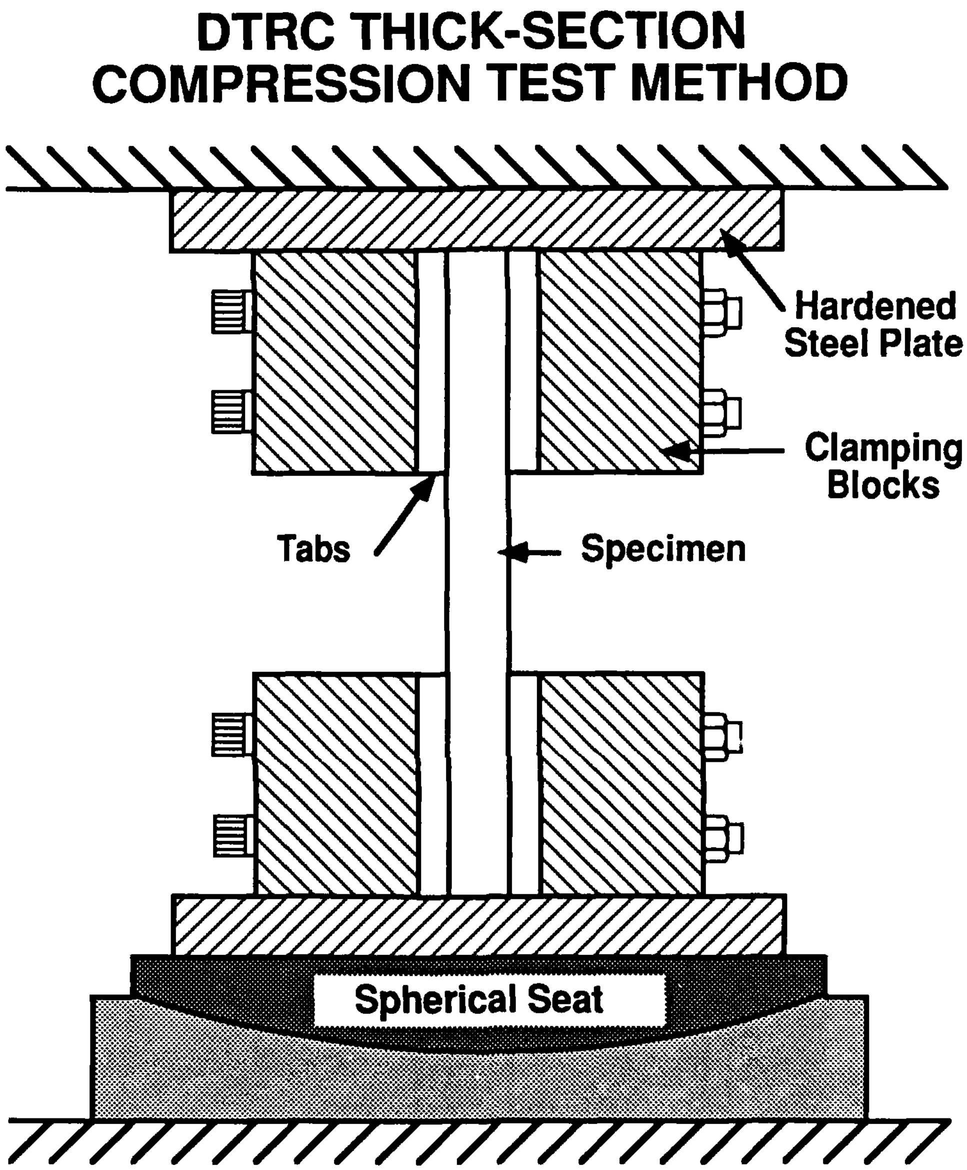

Fig. 1. Schematic of DTRC thick-section compression fixture.

act as load bearing surfaces. A self aligning spherical seat is placed between one end of the specimen and the load machine to assist in aligning the specimen axis and the loading axis.

To load the specimen into the fixture for testing, two mating clamping blocks that comprise one-half of the the fixture are placed on one of the hardened steel loading plates. The specimen is placed into this half of the fixture and when the end contacts the plate the clamping bolts are tightened. The other end of the specimen is clamped into the other half of the fixture using the same procedure. The specimen and both halves of the fixture now become one unit and this unit is placed in the test machine for the application of load. A specimen with the clamping blocks attached to one end is shown in Fig. 2.

The geometry of the specimens for this investigation were adequate to support the the weight of the clamping blocks without alignment rods.

MATERIAL SYSTEMS

Two material systems were evaluated in this investigation. They were chosen to investigate the effects of carbon and glass fiber reinforcements in a common epoxy matrix (Hercules 3501-6). The effect of fiber sizing and the resulting interface chemistry will also affect the compressive response of thick composites however these effects were not quantified in this investigation.

The carbon reinforced prepreg tape was supplied by Hercules

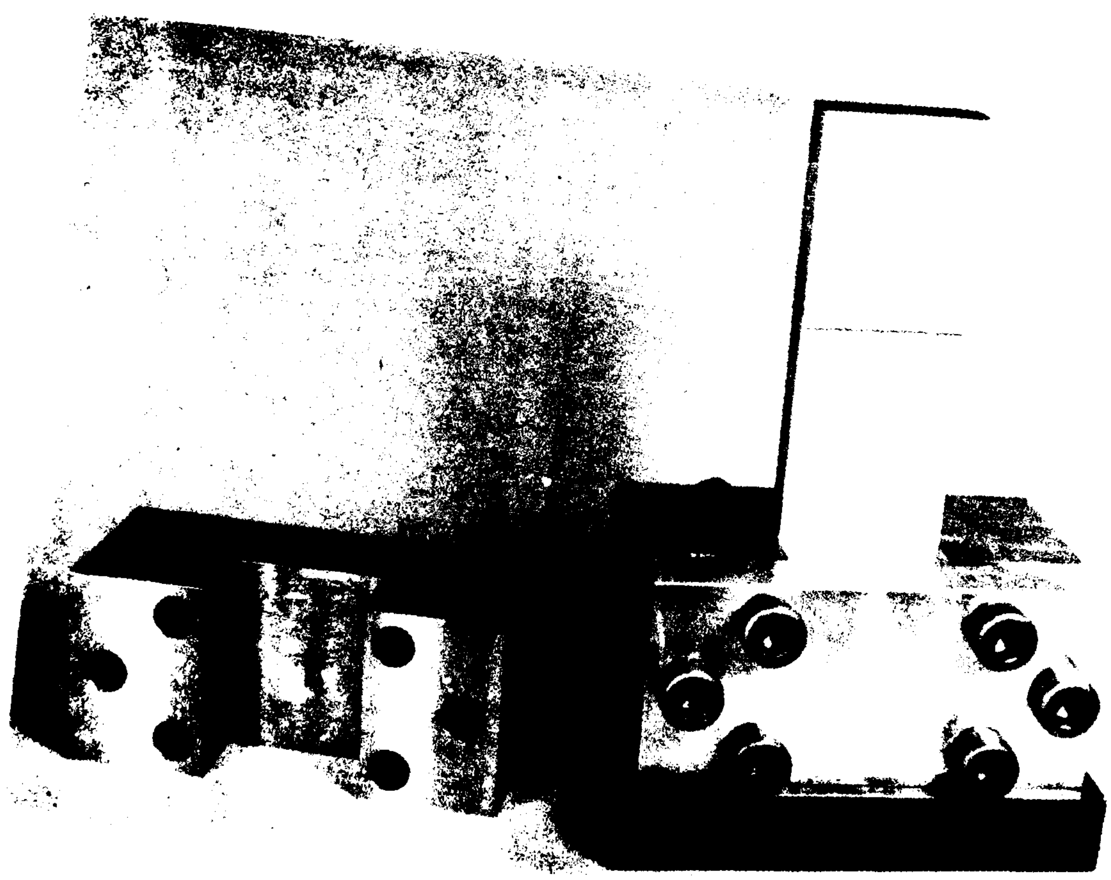

Fig. 2. Photograph of DTRC thick-section compression fixture.

Inc. and was AS4 fiber with 3501-6 350° F epoxy resin. The S2 glass reinforced prepreg was supplied by Fiberite and was S2 glass fiber also with 3501-6 350 F epoxy resin. Both systems were supplied as 12 inch wide prepreg tape and were autoclave cured at DTRC. An autoclave air temperature schedule that was slightly different than those used for thin (< 0.25 inch) epoxy based composites was used. This air temperature was determined from test cures on 96 ply laminates with thermocouples placed in three locations within the test panels.

Following fabrication, samples from each of the four panels (two AS4/3501-6 and two S2 glass/3501-6) were removed and tested for fiber volume fraction (FVF) and void content (ASTM D3171 and D2734). The fiber volume fraction of the AS4/3501-6 panels averaged 60.0 % and the void content averaged 0.34 %. The fiber volume fraction of the S2 glass/3501-6 panels averaged 53.8 % and the void content averaged 0.97 %.

SPECIMEN GEOMETRY

Specimens for this investigation were machined from 12 inch by 12 inch panels, 96 plies thick, of two laminate stacking sequences. The cured laminates were machined so unidirectional $[0]_{96}$ and crossply $[0_2/90]_{16s}$ specimens were available for both the carbon and S2 glass reinforced laminates. The nominal specimen dimensions were 2.00 inches wide by 0.5 inches thick by either 6.5 or 7.5 inches long. The tab length was 2.5 inches so the 6.5 inch long specimen had a 0.75 inch gage length and the

7.5 inch specimen had a 2.5 inch gage length. The specimen geometry is shown is Fig. 3. The average specimen thickness was 0.530 inches for the AS4 specimens and 0.570 inches for the S2 glass specimens. The average tab thickness was 0.090 for the AS4 specimens and 0.070 for the S2 glass specimens.

The length of the specimen gage section was selected on the basis of a Euler column buckling analysis. The materials elastic constants and specimen geometry is used to determine the maximum stable gage length. The equation to determine this permissible length-to-thickness ratio can be expresses as follows:

$$\frac{l}{t} = 0.9069 \left[\frac{E_x}{Y_{ult}} \right]^{\frac{1}{2}}$$

where

l = specimen length	E_x = longitudinal modulus
t = specimen thickness	Y_{ult} = ultimate compressive strength

This equation is derived from reference 2 and includes the assumptions that the specimen acts a as pinned end column, the most conservative end fixity assumption. For a material that has a high longitudinal modulus to longitudinal shear modulus ratio the effects of transverse shear can significantly effect column stability. When the effects of transverse shear are included in the above analysis a more conservative maximum gage length is determined and the expression for length/thickness including this

SPECIMEN GEOMETRY

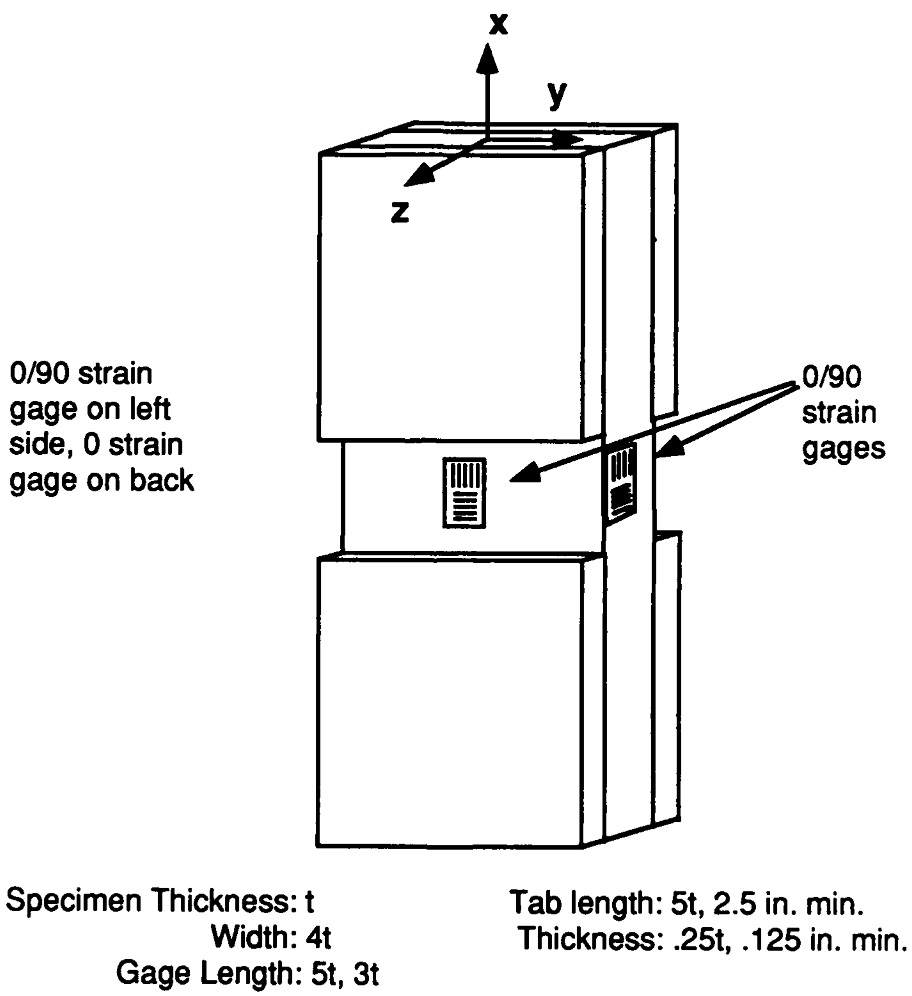

Fig. 3. Specimen geometry, material directions, and strain gage locations.

effect is:

$$\frac{l}{t} = 0.9069 \left[\frac{E_x}{Y_{ult}} \left(1 - 1.2 \frac{Y_{ult}}{G_{xz}} \right) \right]^{\frac{1}{2}}$$

where

l = specimen length

t = specimen thickness

Y_{ult} = ultimate compressive strength

E_x = longitudinal modulus

G_{xz} = through-thickness shear modulus

A plot showing the permissible l/t ratios for an assumed longitudinal modulus and strength is shown in Fig. 4.

Sixteen specimens were fabricated and evaluated for this investigation. Eight specimens were instrumented with seven strain gages and used to monitor strain response on both faces and both free edges of the specimens. The remaining eight were instrumented with two gages (front and back) and used to monitor longitudinal strain on both faces of the specimens. The designations and descriptions for all 16 specimens are shown in Table 1.

THROUGH-THICKNESS POISSON'S RATIO DETERMINATION

The thickness of the 96 ply coupons investigated allowed the direct determination of NUxz with electrical resistance strain gages. NUxz is defined as the through-thickness Poisson's ratio or the negative ratio of the z direction strain to the x direction strain when a uniaxial load is applied in the x direction. Figure 3 shows the x, y, and z specimen directions

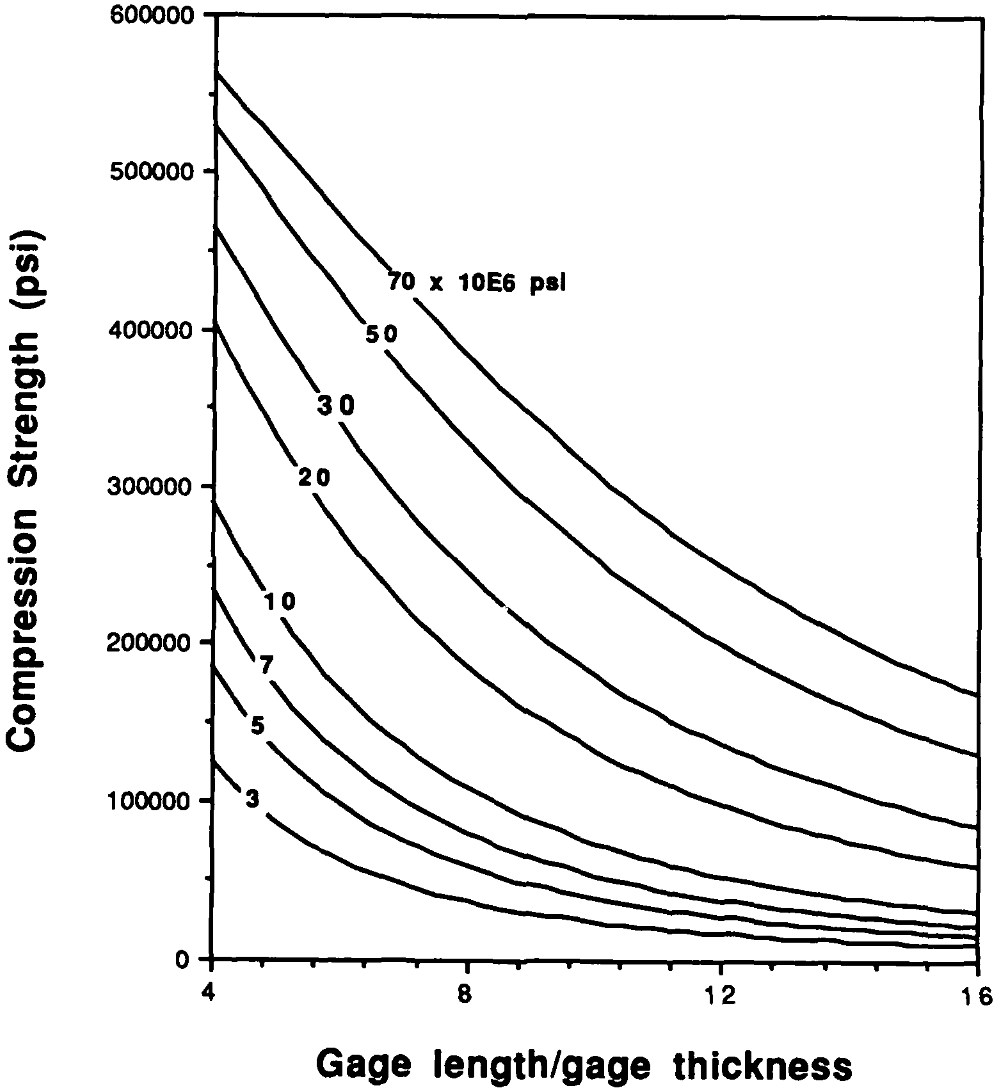

Fig. 4. Permissible length/thickness ratios.

and the strain gage locations. For the $[0]_{96}$ specimens the specimen Poisson's ratio (NUxz) measured is the same as a lamina Poisson's ratio (NU13). For the 8 specimens in which through-thickness strain was monitored strain gages were mounted on the front and back faces and both edges of each specimen. CEA-06-125UT-350 0/90 gages were placed on both edges and one surface of each specimen and a CEA-06-250UW-350 unidirectional gage was placed on the other surface of the specimen. Strain was

Table 1. Specimen Designation

Specimen	Reinforcement	Orientation	1/t Ratio	Comments
C0A	Carbon	$[0]_{96}$	5:1	7 gages
C0B	Carbon	"	5:1	2 gages
C0C	Carbon	"	3:1	7 gages
C0D	Carbon	"	3:1	2 gages
C9A	Carbon	$[0_2/90]_{16s}$	5:1	7 gages
C9B	Carbon	"	5:1	2 gages
C9C	Carbon	"	3:1	2 gages
C9D	Carbon	"	3:1	7 gages
G0A	S2-Glass	$[0]_{96}$	5:1	7 gages
G0B	S2-Glass	"	5:1	2 gages
G0C	S2-Glass	"	3:1	7 gages
G0D	S2-Glass	"	3:1	2 gages
G9A	S2-Glass	$[0_2/90]_{16s}$	5:1	7 gages
G9B	S2-Glass	"	5:1	2 gages
G9C	S2-Glass	"	3:1	2 gages
G9D	S2-Glass	"	3:1	7 gages

monitored with Micromeasurements 2310 conditioner amplifiers and recorded along with load using a digital data acquisition program running on an IBM-AT computer.

Prior to conducting test to failure, a series of five repetitive tests were run to approximately 25% of the ultimate strain to failure. These tests were run to evaluate the fixture and determine repeatability of data from one test to the next. Between each repetition the specimen and fixture were removed from the test machine, the fixture bolts loosened, the specimen was reinserted into the fixture, and the specimen and fixture were placed into the test machine for the next test. For the first three test repetitions edge strains and load were recorded. Load and surface strains were recorded for the final two repetitions. Each specimen was then loaded monotonically to failure while all seven channels of strain and load were recorded.

RESULTS AND DISCUSSION

The results of the repetitive tests run on each of the eight specimens with seven channels of strain indicate that the variation in data from strain gage to strain gage and from test run to test run are within the accuracy of the data from specimen to specimen. The specimen to specimen accuracy is shown in Table 2. with 7.2 % as the largest coefficient of variation for the AS4/3501-6 $[0/0/90]_{16s}$ specimens.

Representative stress-strain to failure plots for each of the four laminate/material combinations are shown in Figs. 5-8. Longitudinal stress-strain plots from the specimens instrumented with three (0/90) gages and one (0) gage contain four curves, one

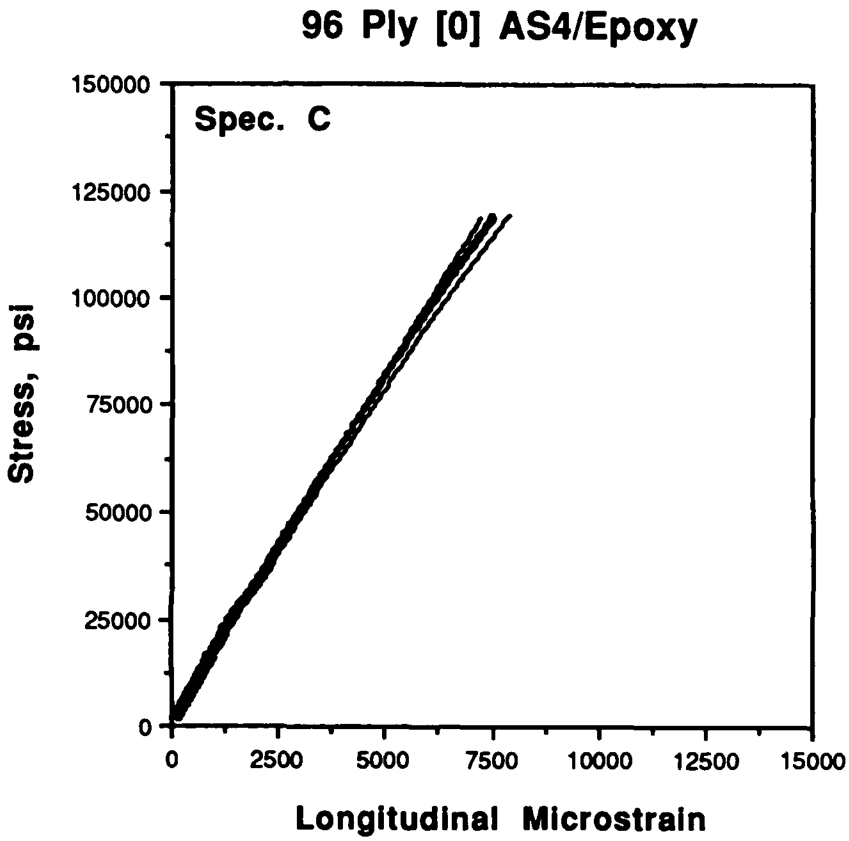

Fig. 5. Longitudinal stress-strain plot - $[0]_{96}$ carbon/epoxy.

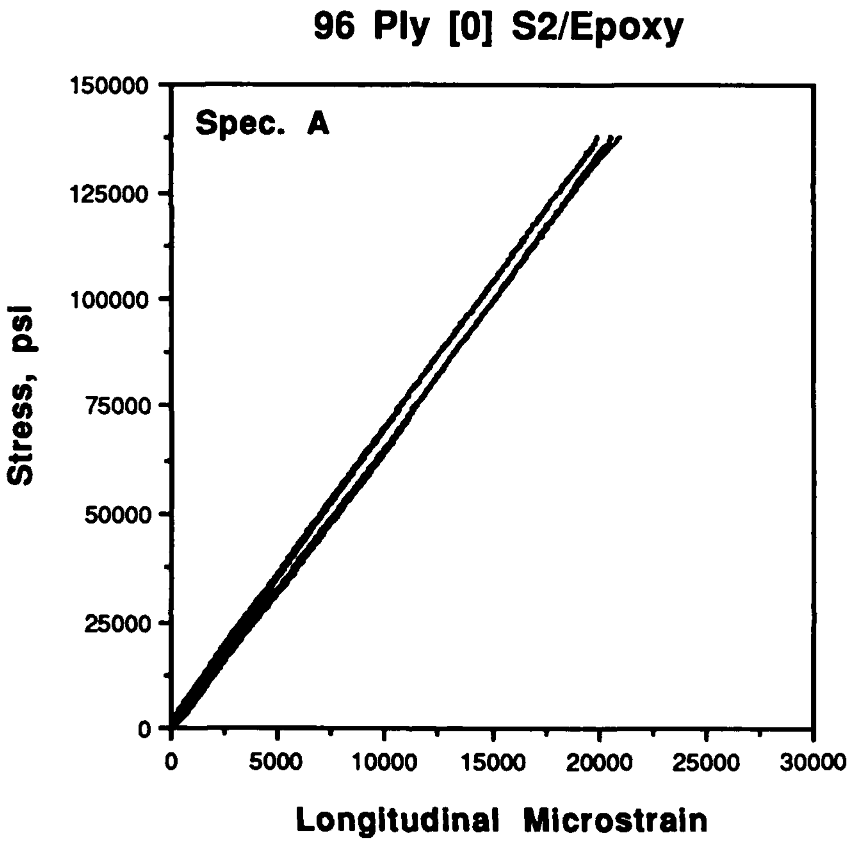

Fig. 6. Longitudinal stress-strain plot - $[0]_{96}$ S2 glass/epoxy.

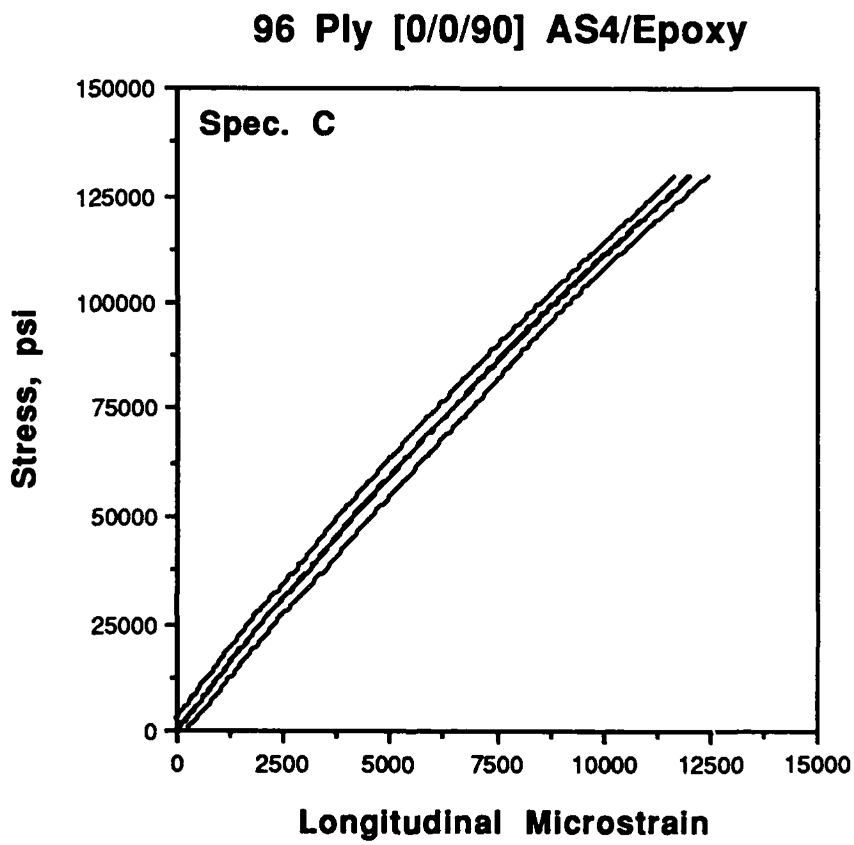

Fig. 7. Longitudinal stress-strain plot - $[0/0/90]_{16s}$ carbon/epoxy.

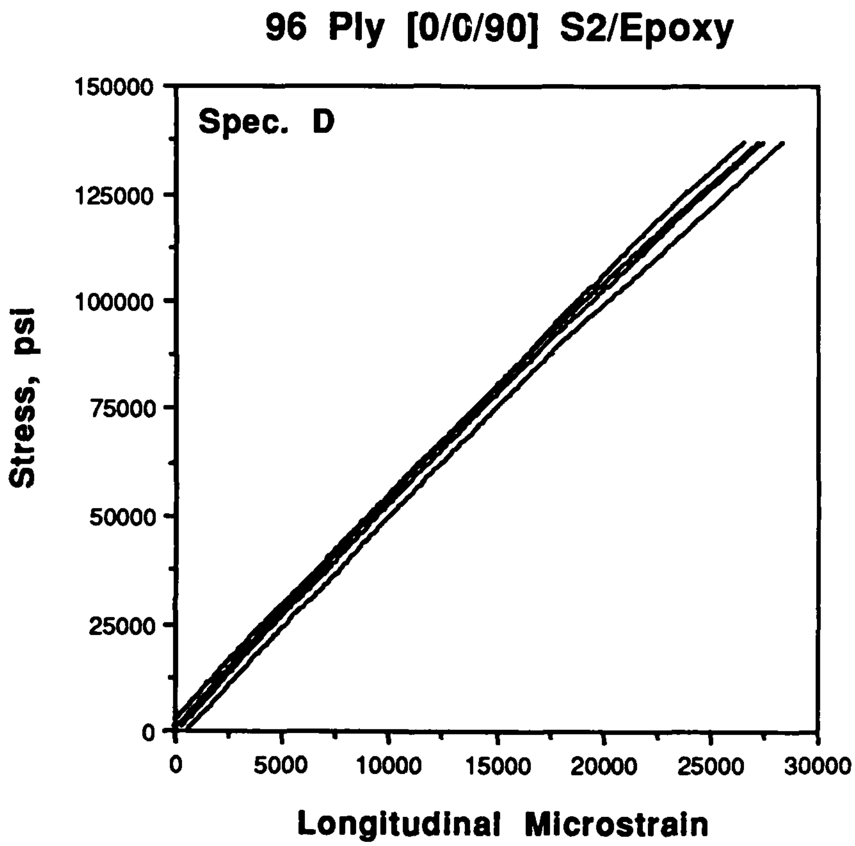

Fig. 8. Longitudinal stress-strain plot - $[0/0/90]_{16s}$ S2 glass/epoxy.

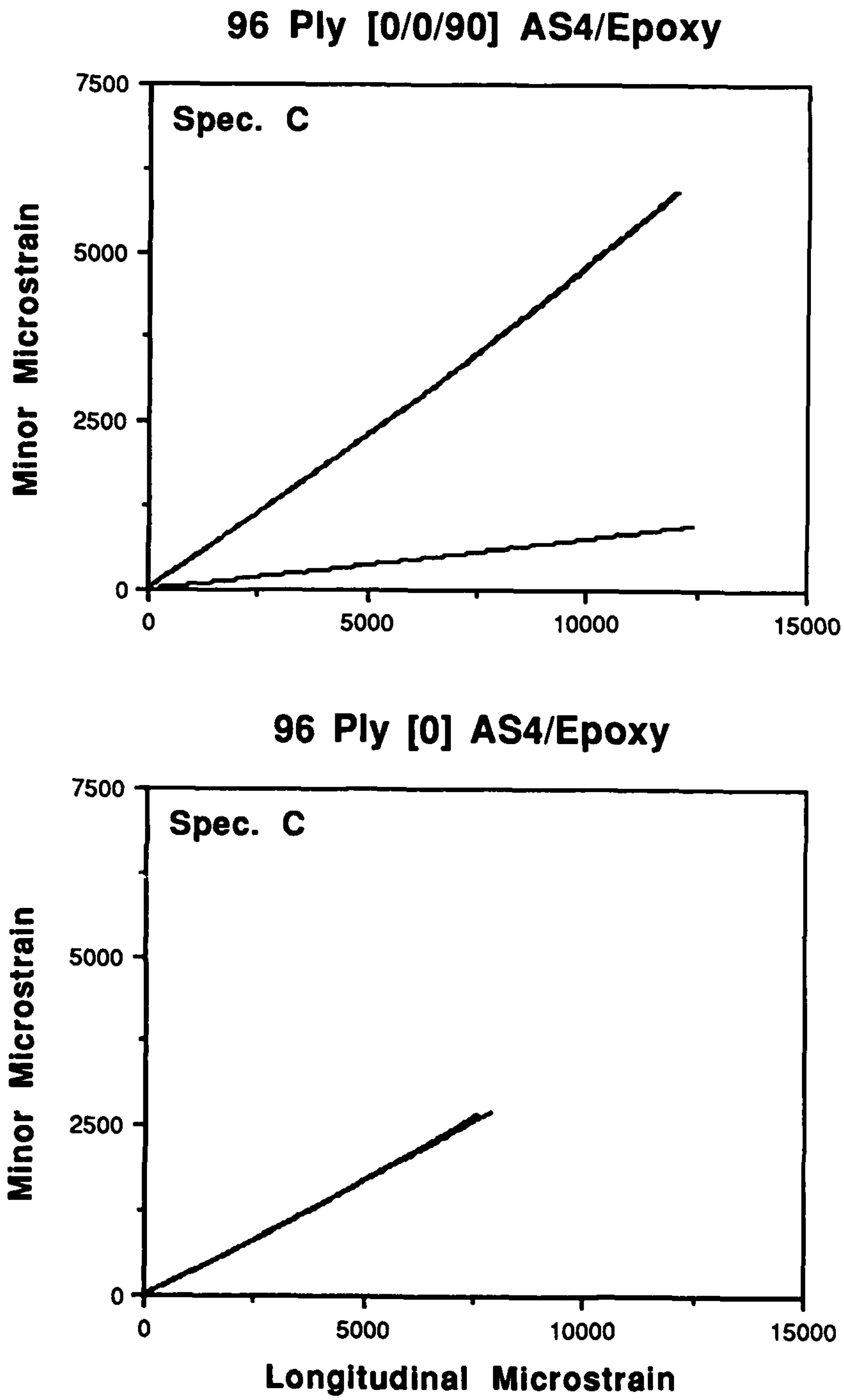

Fig. 9. Through-thickness versus longitudinal strain plot - $[0]_{96}$ and $[0/0/90]_{16s}$ carbon/epoxy.

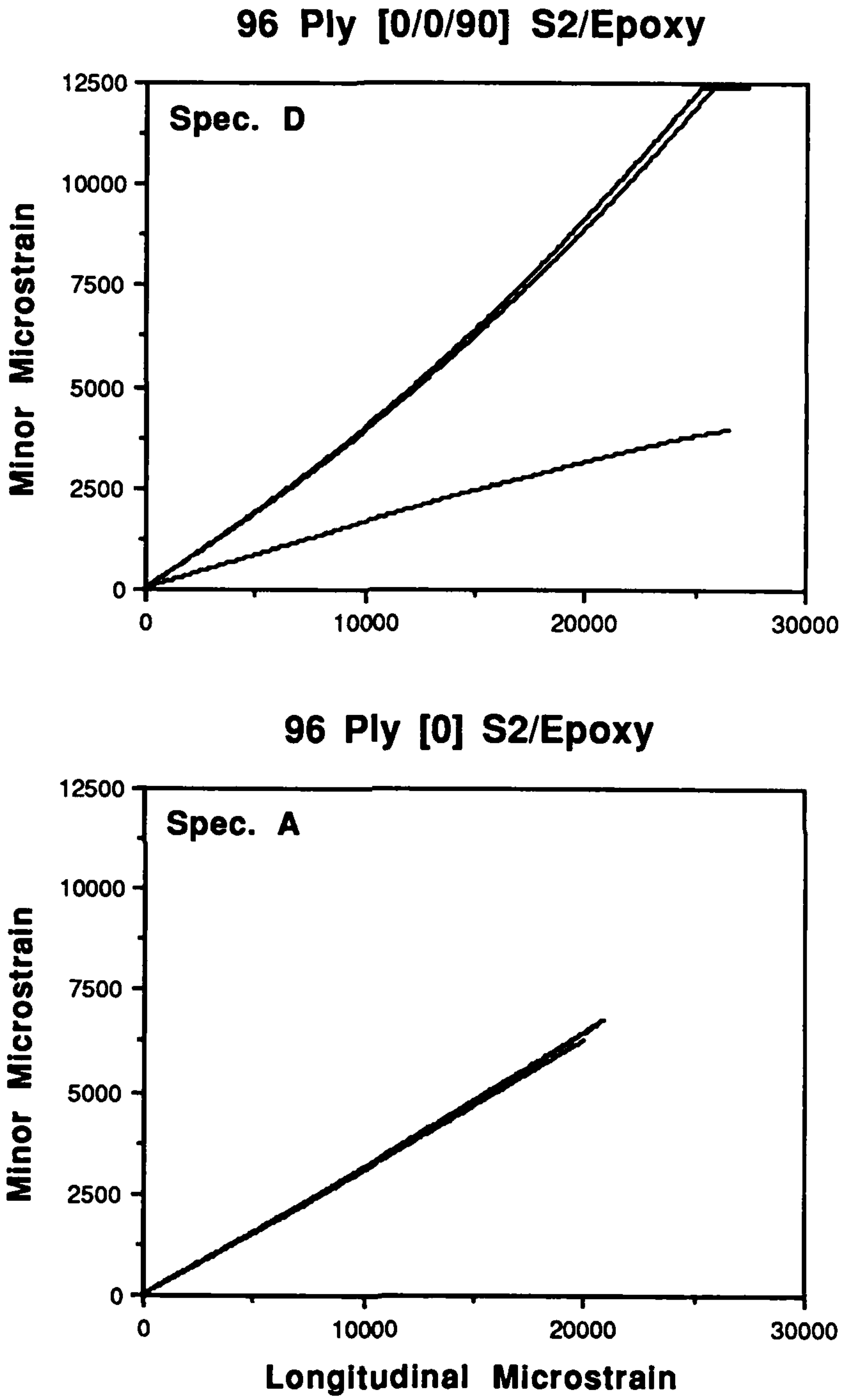

Fig. 10. Through-thickness versus longitudinal strain plot - $[0]_{96}$ and $[0/0/90]_{16s}$ S2 glass/epoxy.

for each longitudinal (0 degree) gage. The longitudinal modulus was determined from the slope of these curves. The Poisson's ratio curves (Figs. 9 and 10) contain three curves each, a longitudinal strain versus transverse strain for the face (0/90) gage, and a longitudinal strain versus through-thickness strain for each of the two edge (0/90) gages. The Poisson's ratio's were determined from the slope of these curves which was determined by taking a secant tangent between 1000 and 3000 longitudinal microstrain.

Tables 2 and 3 summarize the longitudinal moduli and Poisson's ratios for the laminates and materials evaluated. The average longitudinal moduli for each specimen represents the average of either two (2 gages) or fourteen (7 gages) recorded values. The average NU_{xz} for each specimen represents the average of eight recorded values, and the value of NU_{xy} represents the average of three recorded values.

A significant observation from the data in Tables 2 and 3 is that the value of NU_{13} (NU_{xz}) for unidirectional carbon and S2 Glass reinforced laminates is equivalent to NU_{12} (NU_{xy}). When three dimensional material constants are not available the assumption that NU_{13} equals NU_{12} is typically made, and this data shows that the assumption of transverse isotropy is reasonable. This conclusion has been supported in work done by Knight [3].

Unlike NU_{xz} for unidirectional specimens, NU_{xz} for laminates

Table 2. AS4/3501-6 longitudinal modulus and Poisson's ration summary.

	Ave. Long. Mod. (Msi)	C.V. (%)	Ave. NU_{xz}	C.V. (%)	Ave. NU_{xy}	C.V. (%)
			$[0]_{96}$ AS4/3501-6			
C0A	16.70	3.1	.319	2.1	.326	1.9
C0B	16.18	0.9				
C0C	16.84	5.3	.326	1.1	.339	1.6
C0D	15.99	1.5				
Total Ave.	16.68	4.3	.322	2.0	.332	2.8

			$[0/0/90]_{16s}$ AS4/3501-6			
C9A	12.10	2.1	.448	0.5	.071	4.5
C9B	11.88	3.7				
C9C	11.80	4.8				
C9D	11.03	3.3	.452	3.4	.063	2.7
Total Ave.	11.60	5.2	.450	2.4	.067	7.2

C.V. = Coefficient of variation.

Table 3. S2 Glass/3501-6 longitudinal modulus and Poisson's ratio summary.

	Ave. Long. Mod. (Msi)	C.V. (%)	Ave. NU_{xz}	C.V. (%)	Ave. NU_{xy}	C.V. (%)
			$[0]_{96}$ S2 Glass/3501-6			
G0A	6.97	4.0	.300	1.4	.304	0.0
G0B	7.06	2.3				
G0C	7.26	5.2	.312	2.4	.277	3.4
G0D	7.09	1.0				
Total Ave.	7.11	4.7	.306	2.8	.290	5.5
			$[0/0/90]_{16s}$ S2 Glass/3501-6			
G9A	5.61	2.0	.359	3.5	.162	1.1
G9B	5.41	2.1				
G9C	5.62	3.1				
G9D	5.50	3.5	.367	2.8	.152	5.7
Total Ave.	5.55	2.9	.363	3.3	.157	5.0

C.V. = Coefficient of variation.

cannot be directly compared to any inplane lamina or laminate properties. To evaluate the validity of the recorded values a comparison with theoretical predictions of three dimensional elastic constants can be made. Trethewey et. al. [4] recently reviewed several theories for determining the effective three-dimensional properties of layered anisotropic media. All of the reviewed techniques replace a heterogeneous layered media with an equivalent homogeneous anisotropic media and effectively

represent a set a smeared elastic properties. In this report the theory presented by Pagano [5] is reported in detail and encoded, and the elastic properties determined by this theory are the ones that will be used for comparison here.

The input required for the calculation of three-dimensional laminate properties are a complete set of three dimensional lamina properties. The properties used to compare the experimentally and theoretically determined Nu_{xz} are listed in Table 4. Table 5 shows a comparison of the theoretical and experimental elastic constants for the $[0/0/90]_{16s}$ carbon and S2 Glass epoxy laminates studied. The calculated value of Nu_{xz} was forced to correspond the experimental value through selection of input data. In particular, the two values in Table 4 that were varied were NU_{23} and G_{23}. In order to determine the sensitivity of the analysis to the choice of these values a parametric study was performed and the results are shown in Figs. 11 and 12. Both figures show that the value of NU_{xz} is insensitive to G_{23} but very dependent on NU_{23}. The value of NU_{23} necessary to force the match of the theoretical and experimental NU_{xz} data are the ones listed in Table 4. These values of NU_{23} are reasonable since they correspond to values measured experimentally in references [3] and [6]. To determine the value of NU_{23} consistently with the results of this paper $[90]_{96}$ specimens could be fabricated, instrumented and tested in the same manner as the thick compression tests discussed in this report.

Table 4. Lamina input data for three-dimensional elastic constant calculations.

	AS4/3501-6 (60% FVF)	S2/3501-6 (54% FVF)
E_1*	16.7 Msi	7.11 Msi
E_2	1.5 Msi	1.4 Msi
E_3	1.5 Msi	1.4 Msi
NU_{12}*	.33	.30
NU_{13}*	.33	.30
NU_{23}	.47	.38
G_{12}**	.87 Msi	.98 Msi
G_{13}	.87 Msi	.98 Msi
G_{23}	.55 Msi	.55 Msi

* from DTRC thick (0.5 inch thick) compression testing
** from DTRC thin (0.040 inch thick) +-45 tension testing
other values estimated from literature

Table 5. Comparison of theoretical and experimental NU_{xz} results.

	$[0/0/90]_{16s}$ AS4/3501-6 Theor.	Exp.	$[0/0/90]_{16s}$ S2/3501-6 Theor.	Exp.
E_x	11.71	11.60	5.25	5.55
E_y	6.6		3.3	
E_z	1.8		1.5	
NU_{xy}	.075	.067	.127	.157
NU_{xz}	.451	.450	.364	.363
NU_{yz}	.47		.38	
G_{xy}	.87		.98	
G_{xz}	.73		.78	
G_{yz}	.63		.64	

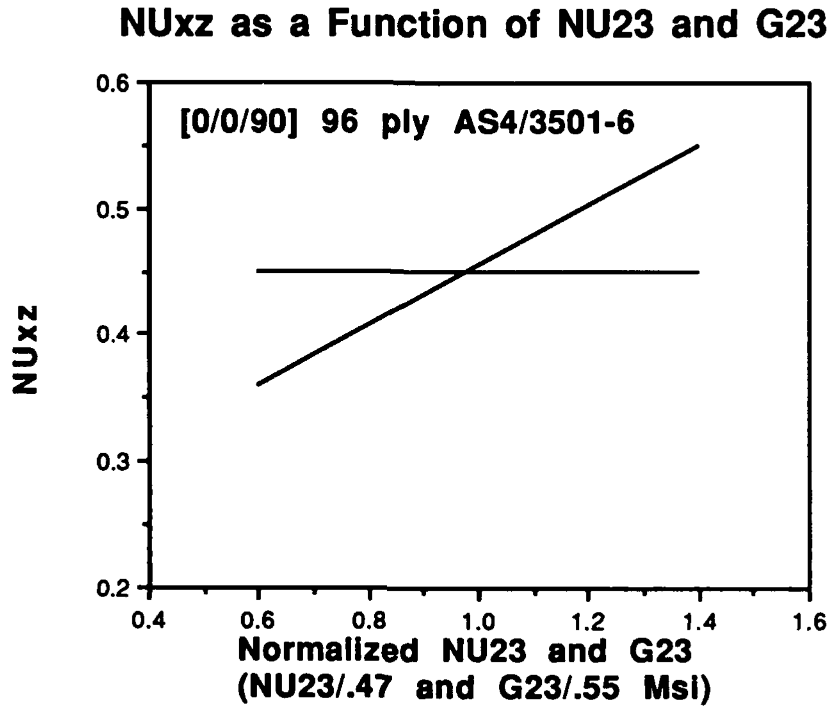

Fig. 11. NU_{xz} sensitivity - carbon/epoxy.

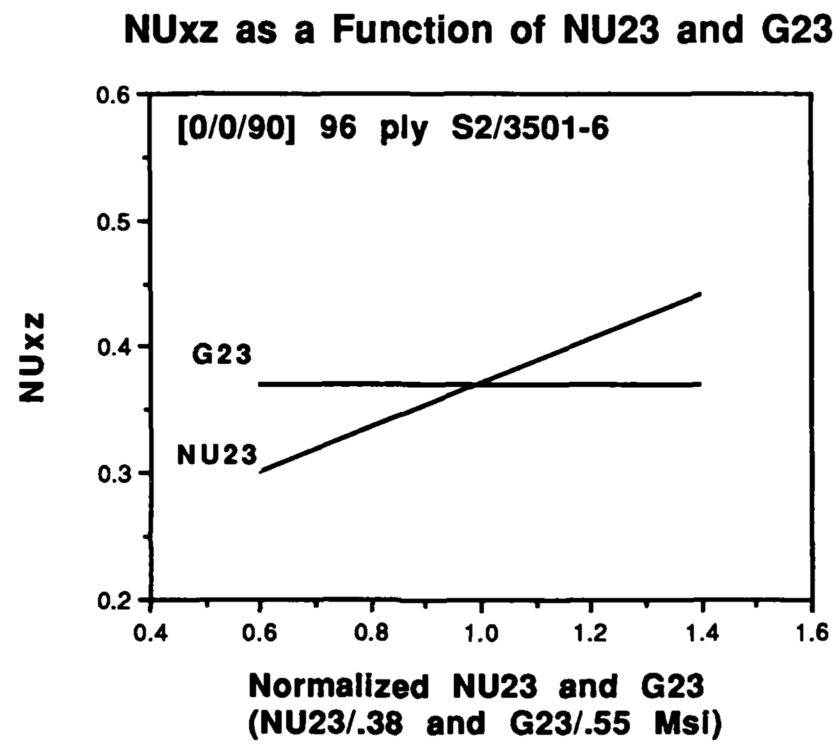

Fig. 12. NU_{xz} sensitivity - S2 glass/epoxy.

The results of this comparison show good agreement between theoretically and experimentally determined three-dimensional orthotropic laminate properties. The benchmark thick-section compression data included here correlates well with a closed-form solution that predicts these laminate properties. Since little experimental three-dimensional elastic constant data is available for composite materials, and since such data is costly to develop, the use of theoretical tools to predict these properties is essential. This initial validation of one such tool indicates it may be used for determining the longitudinal moduli and three-dimensional Poisson's ratios for thick composite laminates.

CONCLUSIONS

A method for determining the through-thickness strain response of thick composites subjected to compressive loading has been developed and used to determine this response of AS4/epoxy and S2 Glass/epoxy composite materials. This data was used to determine the through-thickness elastic constants of the materials and laminate configurations studied.

The accuracy and utility of three-dimensional models for thick composite materials will be directly related to the accuracy of the material properties used as input for these models. Data from this report has shown that for thick-section unidirectional specimens the elastic constants measured showed good agreement with the assumption of transverse isotropy. Furthermore, for the [0/0/90] laminates evaluated, the values

measured for NU_{xz} showed good agreement with values predicted by an analysis that provides all nine elastic constants for orthotropic plates. Additional work validating the prediction of the three-dimensional shear moduli of thick laminated composites using this model is necessary.

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